Ocean Surface Wind Retrieval Using Passive, Polarimetric Microwave Remote Sensing

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LONG-TERM GOAL

The long-term goal of this research is to develop a robust, physically based, and efficient algorithm for retrieving ocean surface wind vectors from fully polarimetric, passive microwave observations. This retrieval scheme is intended for data from the Navy's WindSat and other passive microwave sensors of the future, such as the CMIS instrument on the NPOESS meteorological satellites.

OBJECTIVES

The objectives of this research build on existing work in a variety of publications by Lyzenga, Vesecky and Wang as well as work by others. We first seek to develop an advanced, physically based, forward passive/active microwave ocean model, with rough surface and foam effects. Testing of this forward model would be accomplished by comparing model predictions against existing satellite observations from SSM/I as well as aircraft observations by JPL (Windrad), Georgia Tech. (PSR) and NRL. This model would work with an atmospheric radiative transfer model for microwave emissions and an inversion algorithm to retrieve ocean-surface wind vectors from polarimetric, passive microwave measurements. The retrieval algorithm would be tested and applied to WindSat observations.

APPROACH

Forward Model Improvements and Validation: The emphasis in the present investigation is on estimation of wind direction as well as wind speed from passive microwave measurements. To this end, an emissivity model is required that accurately predicts the dependence of the emitted radiation on azimuth angle, i.e., the angle between the line of sight of the sensor and the wind direction. To estimate how polarimetric brightness temperatures of the ocean surface will vary as functions of observational parameters, we have implemented a two-scale emissivity model based on the second-order small perturbation method (SPM). Our two-scale numerical model predicts the Stokes vector of thermal emission from randomly rough dielectric surfaces described by anisotropic directional ocean wave spectra. The forward model must be computationally efficient, as well as accurate, for operational wind retrievals. Hence, we have devoted significant time to speeding up our numerical model and have developed an even faster analytical model. Validation of the forward model has been achieved through comparison with satellite and aircraft data and is continuing as new data become

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14. ABSTRACT
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available. Current sources of satellite-microwave radiometer data include SSM/I and the microwave imager aboard the TRMM satellite. Airborne polarimetric radiometers include JPL's Windrad and the Georgia Tech. / NOAA ETL Polarimetric Scanning Radiometer (PSR). We compared some of these data with our numerical model and found that there was more variation between the field data sets than between the field data and the model. We are working with NRL to use their 10 GHz field data in the comparisons.

Inversion Algorithm Development: Inversion methods must be both accurate and computationally efficient enough to allow operational wind retrievals in real time. Proper handling of the multi-valued nature of the derived wind vector estimates is also an important factor. We base our inversion methods on WindSat parameters, but make them flexible for application to other instruments, e.g. SSM/I and aircraft instruments. First, we seek accurate retrievals in test cases with simulated data sets and then examine performance using available data sets and empirical models.

WORK COMPLETED

1. **Development of analytical forward model** by approximation of the needed integral using series expansions of integrands. Several orders of magnitude speed increase has been achieved.

2. **Implementation of inversion algorithm improvements** to obtain retrievals from multifrequency measurements with variable available polarizations has been completed. These modifications enable simulations to be carried out that match WindSat measurement parameters in terms of the operating frequencies, available polarizations and expected instrument noise for the individual channels.

3. **Analysis of the uncertainty in wind vector estimates** has been carried out both by using simulation experiments and by computation of the Cramer-Rao lower bound. Differences between the lower bound and the simulation results highlight the effect of the nonlinearity of the problem and the impact of errors due to selection of ambiguous solutions for the wind vector.

4. **Comparisons of errors in wind vector retrievals from single vs. double look measurements** have been examined using simulated data. Results demonstrate advantages of double look measurements in their ability to enable rejection of ambiguous solutions for the wind vector.

5. **Reporting of our results** in journal publications and at major conferences, listed below.

RESULTS

Analytical model for microwave emission from the sea surface: The microwave emissivity of the ocean surface is influenced by both the small-scale and the large-scale surface roughness. The two-scale model described by Yueh (1997) accounts for both length scales, but the large number of computations required for the four-dimensional integration for each Stokes parameter limits it usefulness for wind speed inversion algorithms that involve repeated model evaluations.

We have developed a simplified analytical model for the Stokes parameters describing the polarization properties of the microwave radiation emitted from the ocean surface. The Stokes parameters (T_v, T_h, U and V) are each expressed as a truncated Fourier series in the angle ϕ between the observation

direction and the wind direction, *e.g.*, $T_v(\theta,\phi) = a_0 + a_1 \cos\phi + a_2 \cos 2\phi$. Algebraic expressions are derived for the Fourier harmonic coefficients (a_0, a_1, *etc.*) of the Stokes parameters as functions of the wind speed and the observational angle of incidence. This is accomplished by evaluating the slope integral in the two-scale emissivity model of Yueh (1997) analytically, after expanding the integrand as a Taylor series in the surface slope. The surface slope probability density functions are taken from Cox and Munk (1954) and the ocean wave height spectrum of Durden and Vesecky (1985) is used. Hydrodynamic modulation effects are included to model the upwind-downwind asymmetry in the Stokes parameters. Expressions are derived that allow variations of the four Stokes parameters to be computed as simple functions of the complex permittivity ε of the ocean surface, observational angle of incidence θ, wind direction ϕ and wind speed W. In Fig. 1 we show comparisons with airborne (PSR & Windrad) and space borne (SSM/I) measurements and with our numerical model. We think that this model will find useful application to passive microwave remote sensing of the ocean, in particular to wind retrieval algorithms and to instrument design and evaluation.

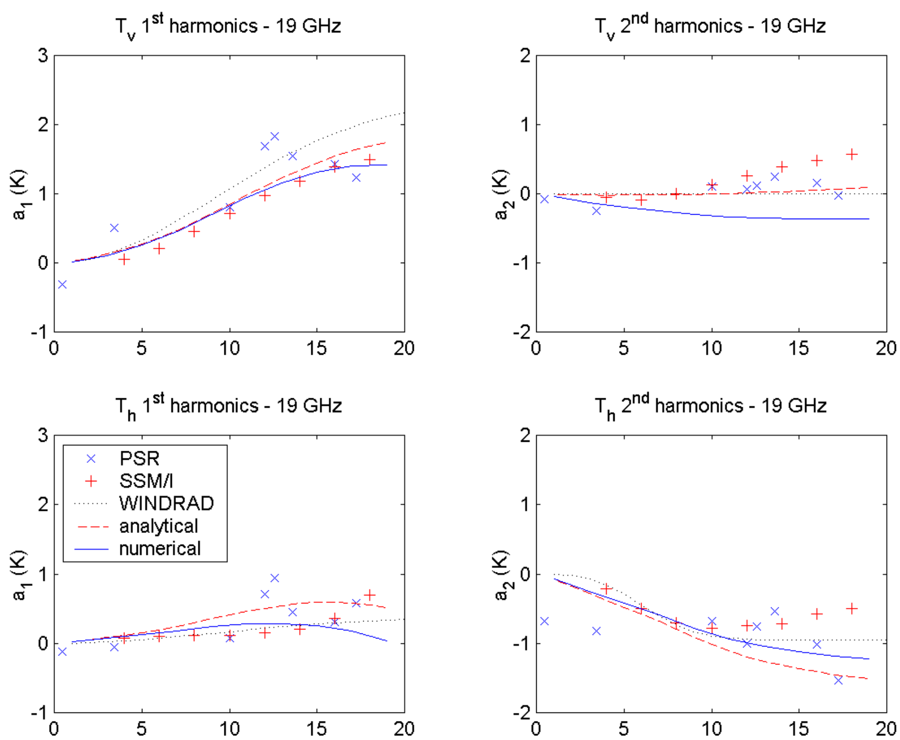

Figure. 1. Comparison of analytical & numerical models (lines) with experimental measurements (symbols) of the Fourier series of the Stokes parameters for frequency = 19 GHz & wind speed = 10 m/s.

Analysis of uncertainties in vector wind retrievals: The inversion algorithm we have developed employs the technique of Maximum Likelihood Estimation (MLE), similar to that described by Piepmeier (2001), to invert the measured sea surface microwave brightness temperatures to obtain estimates of the near surface wind vector. The maximum likelihood solution for the wind vector is obtained by locating the minima of the objective function, $f = \sum_i h_i \left(\hat{T}_{B_i} - T_{B_i}\right)^2$, where $\hat{T}_B$ is the measured brightness temperature, T_B is the predicted brightness temperature for an assumed wind

vector solution and h_i is the inverse of the noise power of the given channel (frequency, polarization and satellite look angle) denoted by the summation index, *i*. In order to estimate the uncertainty of the retrieved wind vector, the Cramer-Rao lower bound on the error variance may be computed. This bound is given by

$$V = \left\langle \left[\left(\frac{\partial T_B}{\partial x} \right)^T R^{-1} \left(\frac{\partial T_B}{\partial x} \right) \right]^{-1} \right\rangle ,$$

where *x* denotes the vector of inputs to the system, i.e., wind speed and direction, and *R* is a diagonal matrix whose elements contain the noise variance of the brightness temperature measurements. The angular brackets denote the ensemble average and the *T* and -1 superscripts indicate the matrix transpose and inverse operations, respectively. Computation of the derivatives is facilitated by assuming the harmonic expansion for the brightness temperatures described above and approximating the harmonic coefficients by a polynomial expansion in wind speed. The coefficients of the expansion are determined, for a given sea state, by the forward model.

In addition to computing the lower bound on the error variance, we carried out Monte-Carlo simulations as an alternative method for predicting the expected uncertainties. Differences in results obtained using the different methods are expected for two reasons: first, because the Cramer-Rao lower bound does not include the effect of bias terms that arise due to the nonlinearity of the system; and second, because the lower bound does not include the effect of errors due to the selection of ambiguous solutions. Results of this analysis, shown in Figures 2 and 3, demonstrate the impact of selection of ambiguous solutions on the accuracy of wind retrievals and the improvement obtained using measurements where two looks from different azimuthal directions are available. For the results presented here, measurement parameters were selected to match those of the WindSat instrument, 16 channel (3 frequency polarimetric, 2 frequency dual linear polarization) radiometer measurements. The noise powers for the given channels were set equal to the expected receiver noise for the WindSat instrument and did not include uncertainty due to atmospheric effects or limitations of the forward model. For the single look case, the satellite look direction was 45°. For the two look case, the look directions were 45° and 135° (angles relative to satellite ground track).

We anticipate that these results and the corresponding analyses techniques we have developed will aid in error estimation of vector wind retrievals from real data sets such as those expected to be available in the near future from WindSat and other future instruments and aid in the continuing development of vector wind retrieval algorithms.

IMPACT/APPLICATION

The impact of an accurate physical model for active and passive microwave characteristics of the ocean surface would be truly striking. While empirical models are very useful, they are limited to the environmental and observational conditions under which the data were collected and unmodeled variables are likely to cause errors. Hence, an accurate physical model could relieve some limitations on operational wind retrievals. The most important impact of our research would be in providing accurate wind field retrievals for the WindSat satellite, as well as other future active and passive microwave sensors. In addition, an accurate microwave ocean model would be useful for instrument design, estimating errors and for interpolating and extrapolating empirical data for empirical model functions. Our efforts in the area of algorithm development and error analysis may help to further

illuminate the potential problem of large errors or unreliable results due to the presence of ambiguous solutions and suggest a partial solution to the problem that is both effective and reasonably efficient computationally.

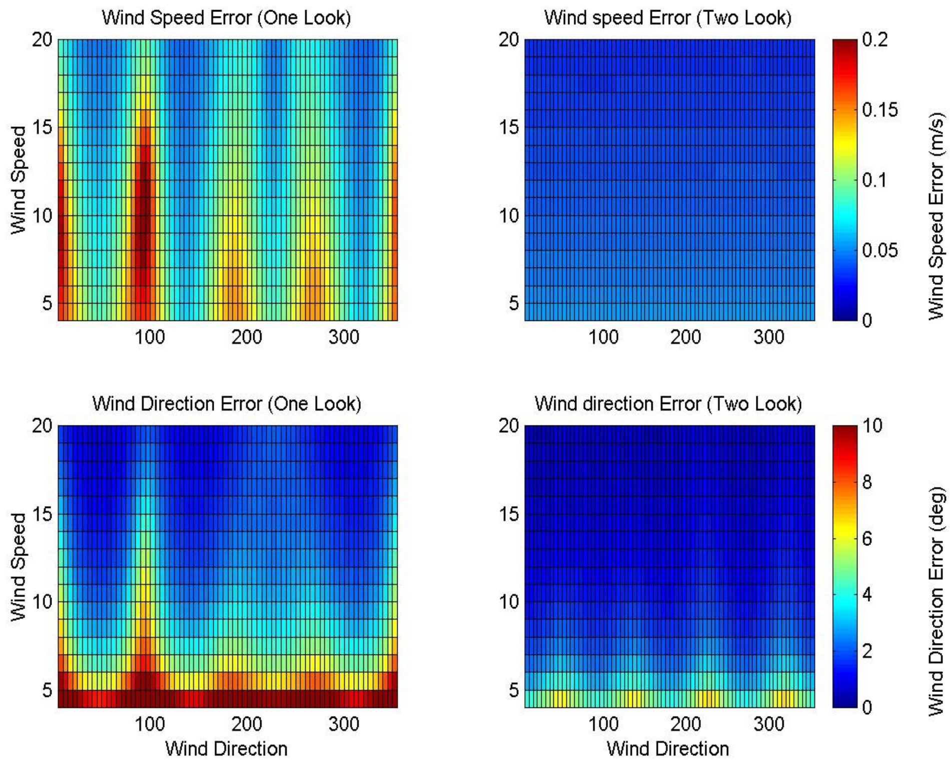

Figure 2. Plots of the Cramer-Rao lower bound for the wind speed and direction error standard deviation for single and double look wind vector retrievals.

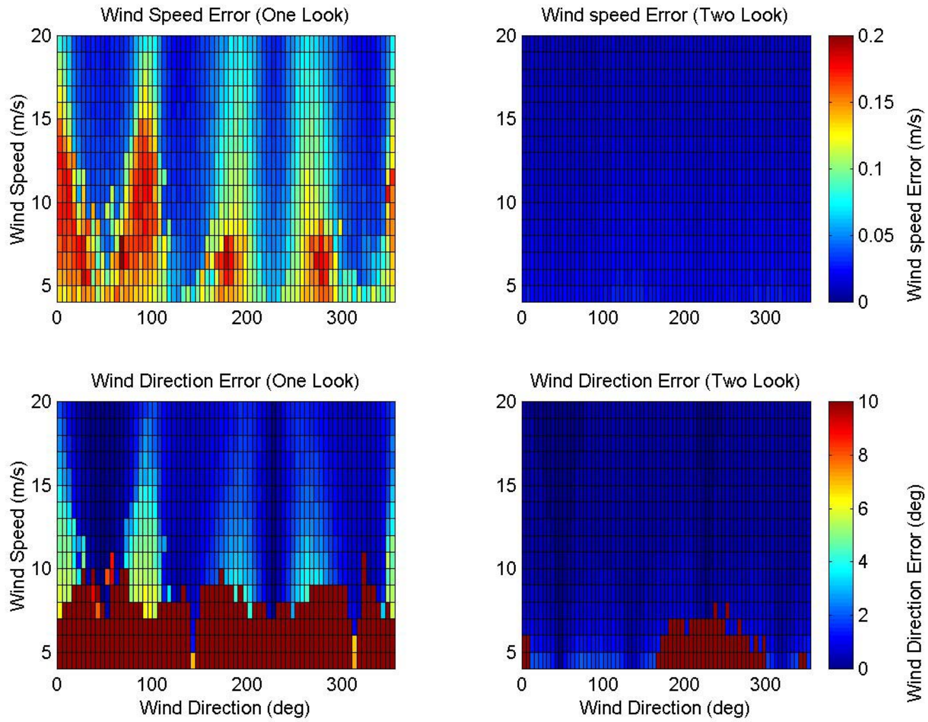

Figure 3. Plots of the standard deviation of errors observed in vector wind retrievals from simulated data for single and double look cases showing effect of errors due to ambiguous solutions.

TRANSITIONS

We anticipate that our work will transition to the meteorological remote sensing community to enable more accurate wind vector retrievals for the Navy's WindSat and other future satellite sensors.

RELATED PROJECTS

The most important related project is the Navy's WindSat project that successfully launched a fully polarimetric passive microwave sensor in January 2003.

PUBLICATIONS and PRESENTATIONS

Laws, K.,E. , D. Lyzenga, J. Vesecky and D. Wiberg, Estimation of the error variance of vector wind estimates from fully polarimetric measurements of ocean surface brightness temperature, Oral presentation, American Geophysical Union, Ocean Sciences Meeting (2002)

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